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Interactions and Limitations of Primary Dust Controls for Continuous Miners

By J. F. Colinet, J. J. McClelland, and R. A. Jankowski

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	mg/m^3	milligram per cubic meter
ft	foot	min	minute
g/min	gram per minute	mm	millimeter
gpm	gallon per minute	μm	micrometer
h	hour	psi	pound (force) per square inch
in	inch	s	second
L/min	liter per minute		

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INTERACTIONS AND LIMITATIONS OF PRIMARY DUST CONTROLS FOR CONTINUOUS MINERS

By J. F. Colinet,[1] J. J. McClelland,[1] and R. A. Jankowski[2]

ABSTRACT

Laboratory tests were conducted by the U.S. Bureau of Mines to determine respirable dust reduction effectiveness of and interaction between face airflow and water sprays for a continuous miner. Increases in exhausting face ventilation from 3,000 to 9,000 cfm, in waterflow from 15 to 35 gpm, and in water nozzle operating pressure from 80 to 200 psi were evaluated. Results indicated that airflow had the greatest individual impact on reducing dust levels, with concentrations at return and operator sampling locations reduced by as much as 57% and 99%, respectively.

Regression modeling was utilized to predict dust concentrations over the range of values tested for the control parameters. Interactions between the control parameters were significant and often defined an optimum level where further increases in that parameter failed to produce additional dust reductions. Increasing airflow to 8,400 cfm, waterflow to 25 gpm, and water pressure to 140 psi typically reduced dust concentrations at operator and return locations. Application of a control parameter above these levels can provide additional dust reductions if used in conjunction with appropriate levels of the other two control parameters. Otherwise, higher operator dust levels may result and can be attributed to increased rollback and/or airflow turbulence.

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INTRODUCTION

Given the known health hazards associated with breathing respirable coal and silica (quartz) dust generated during mining, mine operators are continually seeking ways to minimize worker exposure. Ventilation and water sprays are the primary means used to control dust liberation and worker exposure. Ventilating air dilutes the generated dust and also carries airborne dust away from workers. Water applied through machine-mounted spray systems suppresses dust entrainment and also removes dust that has become entrained in the ventilating air. However, the use of air and water to control dust has limits. From an operations viewpoint, increases in these control parameters add to the financial cost of producing coal and at some level may aggravate other conditions in the mine (wet floor and increased belt wear) or outside the mine (acid mine water and increased noise from larger ventilation fans). From a health and safety viewpoint, continual increases in these control parameters do not ensure further reductions in dust levels. Thus, the application of these control parameters should be planned and undertaken with care to maximize effectiveness.

The objective of this program was to determine those levels of air quantity, water quantity, and water pressure that result in the lowest dust levels at the miner operator and return locations. Information about the interactions between control parameters and maximum effective limits for each parameter was of particular interest. To assist in identifying the impact of changing the levels of the control parameters, a computer program was written that calculates predicted dust concentrations for user-specified combinations of control parameters. The program is provided in appendix A.

MINE TEST GALLERY

All tests were conducted in the full-scale, simulated mine gallery at the Pittsburgh Research Center. The mine entry was 18 ft wide with a mining height of 80 in. The face area simulated a 15-ft-deep box cut, with an approximately 6-ft-wide by 15-ft-long slab remaining on the left side of the entry. Figure 1 shows the mine layout as used for this test program.

A full-scale wooden model of a Joy[3] 14CM continuous miner was used in testing. The miner was positioned within 1 ft of the face in the box cut for a series of box cut tests and subsequently relocated to the left side of the entry for a series of slab cut tests. The cutter boom of the miner was in a raised position during the first half of each test period and then lowered for the second half. The cutting head of the miner was operated throughout all tests.

For this program, the miner was equipped with two spray manifolds. One manifold was mounted on top of the cutter boom, with the second manifold mounted on the underside of the boom. The top manifold was drilled and tapped to hold 12 spray nozzles, equally spaced across the length of the manifold (fig. 2). The underboom manifold contained six equally spaced spray nozzles. All nozzles produced hollow-cone spray patterns and were oriented perpendicular to the face. A pressure gauge was also installed on each spray manifold for visual verification of the water pressure at the nozzles.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Two minieductors utilized compressed air at 50 psi to transport dust through two hoses into the face area of the mine gallery. A pressure gauge and regulator were installed in the compressed air supply line to monitor and control the air feeding the minieductors. The compressed air entering the minieductors passed through a venturilike section in the eductors, which induced the dust feed into the airstream. Both discharge hoses from the eductors were mounted on the model miner in the area of the ripper chain. One hose discharged in front of the right cutter drum, while the second hose discharged in front of the left drum.

The minieductors were fed a blend of minus 50-μm dust containing 90% bituminous coal and 10% quartz dust, by weight. Previous research[4] has shown that this size particulate is representative of the airborne dust found on continuous mining operations. Both types of dust were purchased from commercial suppliers and then mixed. For these tests, a screw feeder discharged approximately 28 g/min into the eductors.

Ventilation for the mine gallery was provided by an exhaust fan capable of supplying approximately 18,000 cfm of air to the face. The return airway in the mine gallery was equipped with an adjustable regulator to control the quantity of air reaching the face.

[4]Ramani, R. V., J. M. Mutmansky, R. Bhaskar, and J. Qin. Fundamental Studies on the Relationship Between Quartz Levels in the Host Material and the Respirable Dust Generated During Mining, Volume I: Experiments, Results, and Analysis. BuMines OFR 36-88, 1987, 179 pp.; NTIS PB 88-214325.

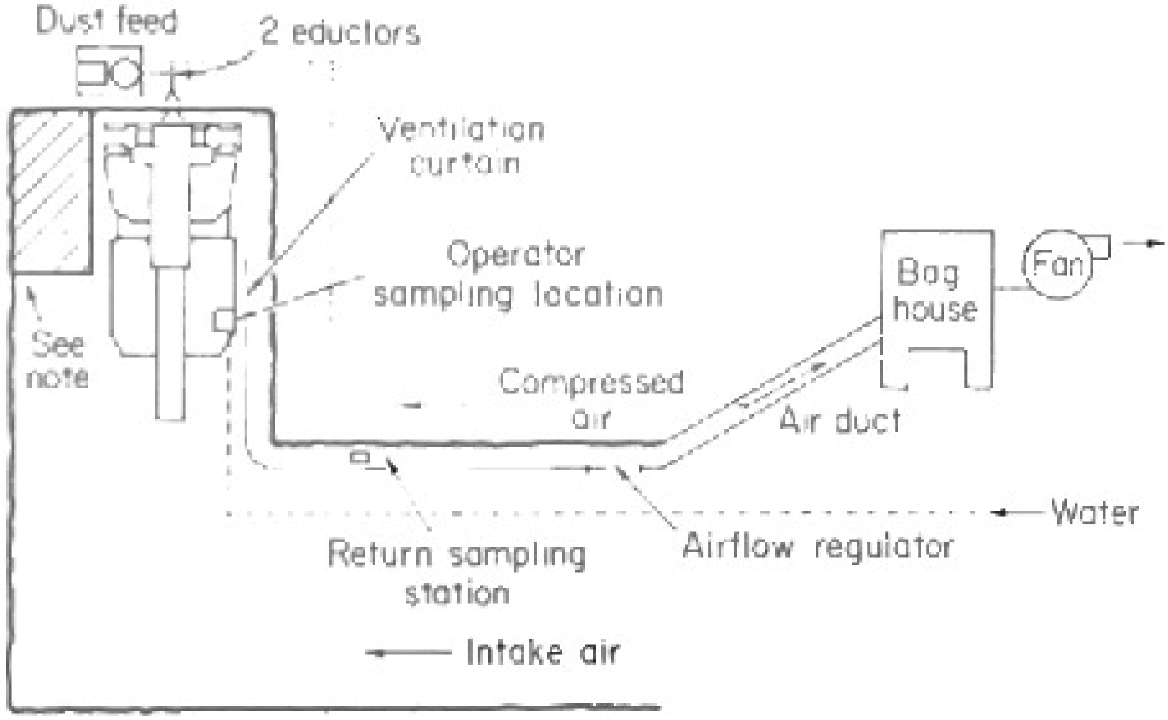

Figure 1.–Schematic of mine test gallery. Note: Miner is shown in box cut; left front of miner is placed at arrow for slab cut.

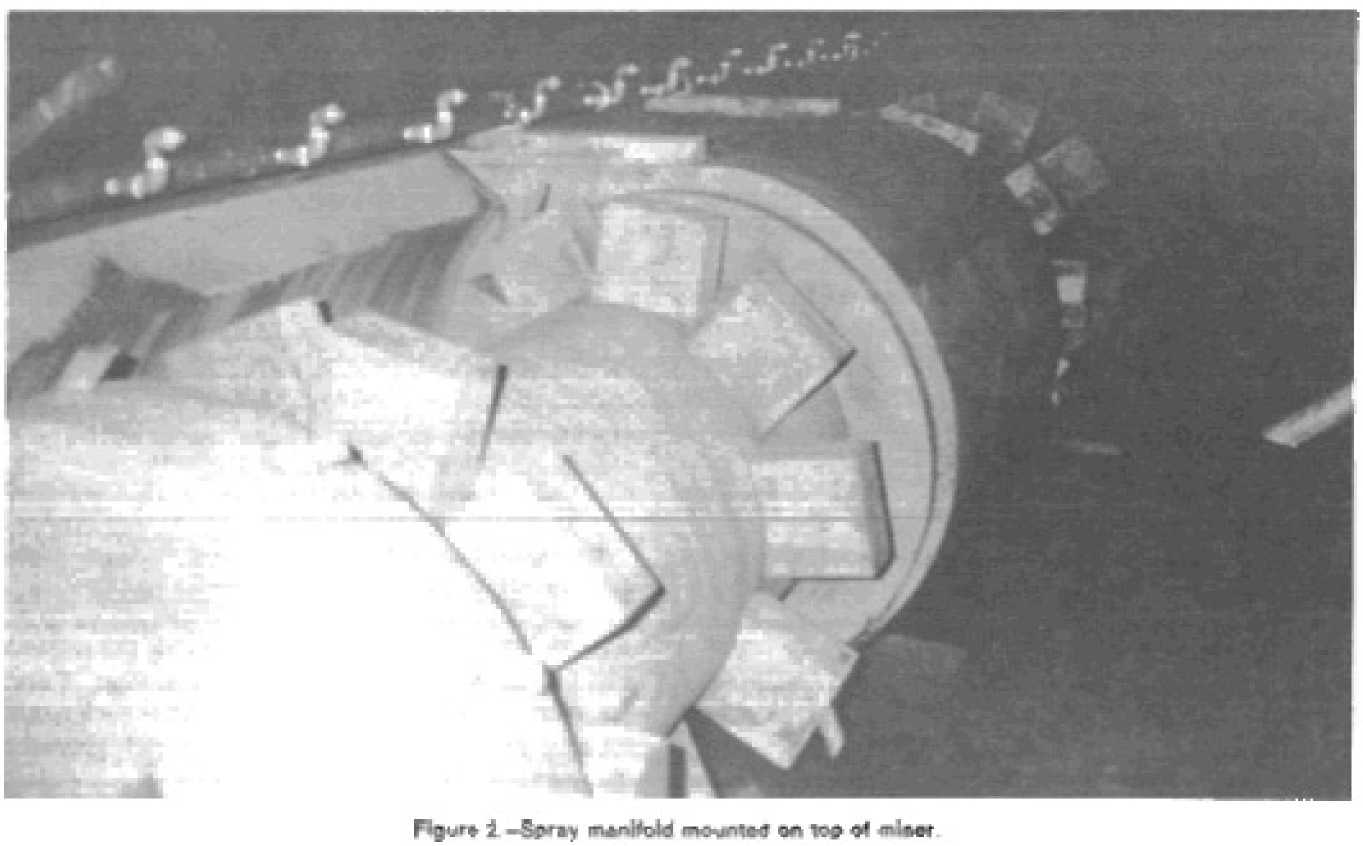

Figure 2.–Spray manifold mounted on top of miner.

Water supplied to the miner water sprays was passed through a booster pump to attain the quantity and pressure requirements. A totalizing meter and a flowmeter were installed in the water supply line to the miner. The totalizing meter was used to calculate an average waterflow for each test. The total gallons, determined from readings taken at the beginning and end of each test, was divided by the test time to obtain the average flow rate, in gallons per minute. The flowmeter provided a real-time flow measurement in the form of an electrical output proportional to waterflow rate. This output was transmitted to a multichannel strip chart recorder in the mine gallery control room for continuous monitoring of the waterflow rate throughout each test.

A pressure transducer was installed at each spray manifold on the miner to measure nozzle operating pressure. These transducers produced electrical output signals proportional to the water pressure. These output signals were directed to the strip chart recorder in the control room to continuously monitor the operating pressure of the spray nozzles. Pressure regulators were installed in the water line on the miner to provide control for obtaining the desired pressures.

TEST PROCEDURES AND EQUIPMENT

A series of tests was conducted to evaluate the effect of changing water quantity, water pressure, and air quantity on the dust levels at the miner operator's location and in the return. The range of interest for these control parameters was 15 to 35 gpm, 80 to 200 psi, and 3,000 to 9,000 cfm, respectively. Tests were to be conducted at the low, midrange, and high levels for each control parameter. Tests were to be conducted in the box and slab cut positions, with three replicates for each test condition. Consequently, a total of 162 tests would be needed to satisfy the three-level factorial design described above. To reduce the required number of tests while still obtaining the desired information, a face-centered-cube experimental design[5] was adopted. This limited the test conditions to those shown in table 1. The test representing the midrange levels (25 gpm, 140 psi, and 6,000 cfm) is repeated three times to satisfy the statistical requirements of the chosen experimental design. Utilization of this design reduced the number of tests to 102.

In order to fulfill the water application needs specified in the test plan, four different sizes of spray nozzles were required. Spraying Systems Co. BD2, BD3, BD5, and BD8 hollow-cone spray nozzles were used as needed to obtain the desired waterflow and water pressure combinations.

Prior to each test, the appropriate nozzles were installed in the spray manifolds on the miner. The pressure regulator was then adjusted to set the desired water pressure for the test. This pressure was visually checked on the miner and then monitored throughout the test with the strip chart data in the control room.

A handheld vane anemometer was used to measure the air velocity at the inby end of the return line brattice to determine the face air quantity. Adjustments to the return regulator were made as needed to obtain the desired quantity.

Table 1.—Levels of dust control parameters tested[1]

Waterflow, gpm	Water pressure, psi	Airflow, cfm
15	80	3,000
15	80	9,000
15	140	6,000
15	200	3,000
15	200	9,000
25	80	6,000
25	140	3,000
25	140	6,000
25	140	6,000
25	140	6,000
25	140	9,000
25	200	6,000
35	80	3,000
35	80	9,000
35	140	6,000
35	200	3,000
35	200	9,000

[1]3 tests were conducted in the box and slab cut positions for each combination of control parameters.

Gravimetric dust samplers, operated at 2 L/min, were used to sample respirable dust concentrations in the operator's cab and in the return. These samplers were operated with 10-mm cyclones so that only the respirable dust fraction was deposited onto a 37-mm filter. Prior to use, filter preweights were obtained. After each test, the net dust weight and sampling time for each gravimetric filter were obtained for later analysis.

[5]E. I. du Pont de Nemours & Co., Quality Management Services. Strategy of Experimentation. 1988, pp. 11.1-11.37.

For each test, two gravimetric samples were collected in the operator's cab and six samples were collected in the return. At the operator sampling location, two cyclone filter units were suspended from a hanger in the approximate breathing zone of the operator. Return cyclones were located in groups of two at approximately 20, 40, and 60 in from the roof.

Real-time aerosol monitors (RAM), instantaneous sampling instruments, were used to supplement the gravimetric samplers. Each RAM is equipped with an internal pump to draw air through a 10-mm cyclone preseparator at a flow rate of 2 L/min. The dust-laden air passes through a light source, and the amount of light deflection is representative of the dust concentration. These dust concentrations are displayed on the RAM sampler and can also be outputted for external recording. Data loggers were used to record the dust concentrations for later analysis on a computer. In addition, the output was transmitted to the multichannel strip chart recorder in the control room for monitoring throughout the tests.

One RAM was positioned adjacent to the gravimetric samplers at the operator location, while three RAM's were used in the return. The cyclone preseparator for each RAM was suspended between the two cyclones used for gravimetric sampling and connected to the RAM with Tygon rubber tubing. Figure 3 shows the sampling equipment as used in the operator's cab. The RAM samplers were operated concurrently with the gravimetric samplers during each 2-h test. In addition, the RAM samplers were operated during a 15-min "base period" before the start of each test. Prior to the base period, the face ventilation had been set, the dust injection system started, and the dust cloud allowed to stabilize. The RAM samplers then recorded the base dust concentrations over a 15-min period as a means of monitoring test-to-test fluctuations in the dust feed in the absence of water sprays.

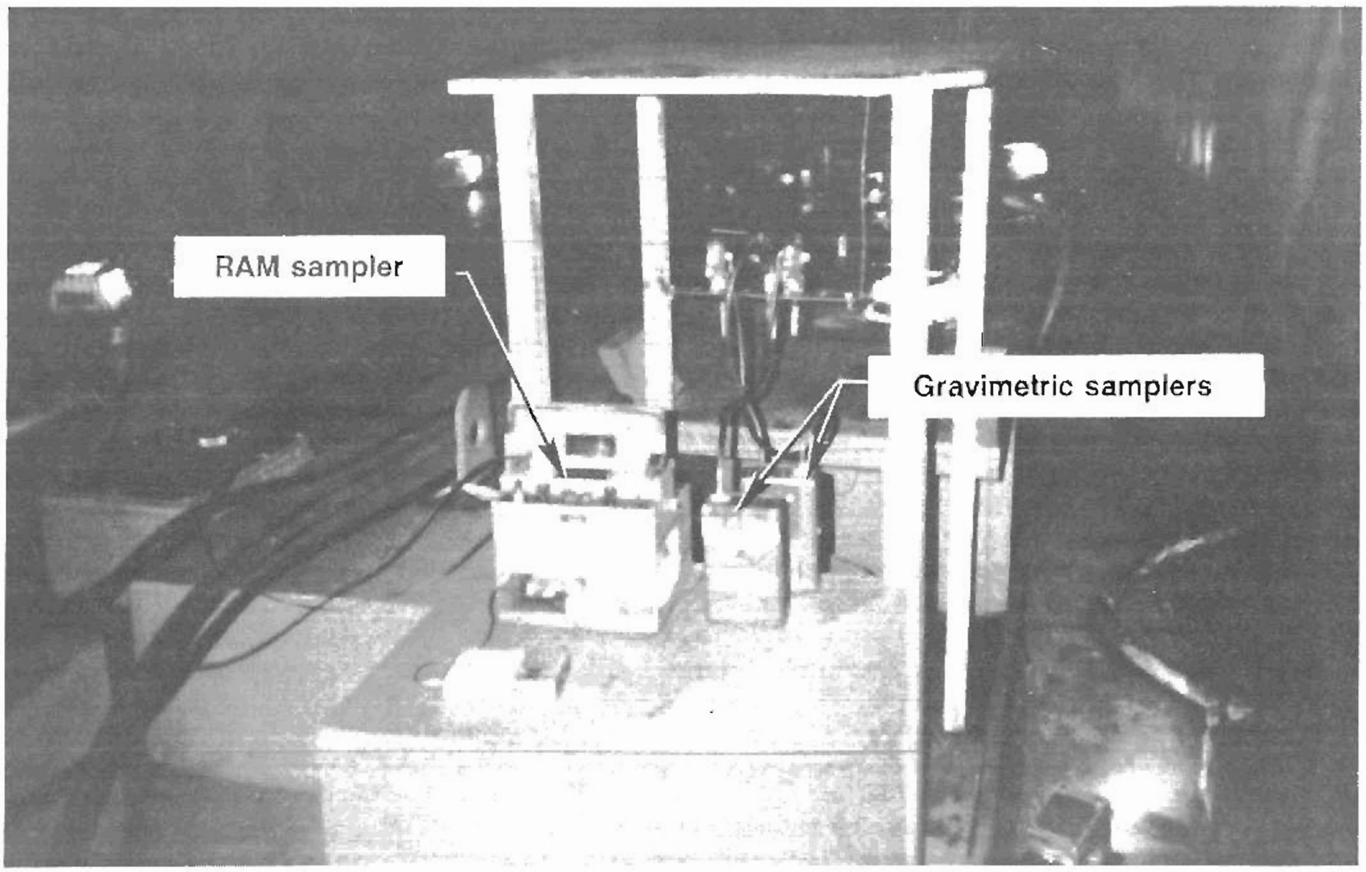

Figure 3.—Sampling equipment at operator's position.

DATA ANALYSIS

RAM logger data were downloaded onto a personal computer and a software package was used to calculate average dust concentrations for the base and test periods. Figure 4 provides an example of the typical output from the RAM. The dust weights and sampling time obtained for the gravimetric samples from each test were entered into a spreadsheet file. The spreadsheet software calculated a dust concentration for each sample. The individual dust concentrations for the six return samples were combined to calculate an average return concentration for each test. Likewise, an average operator's concentration was calculated from the two samples in the cab. The average gravimetric dust concentrations (operator and return sampling locations) from each test were then normalized for fluctuations in dust feed. Each average gravimetric concentration from a test at a specific airflow and location (for example, first test in the box cut at 3,000 cfm) was multiplied by a normalizing ratio. This ratio was calculated by dividing the average RAM return base dust level for all tests at the same location and airflow by the RAM return base dust level from the test being normalized. Tables B-1 through B-4 (appendix B) contain the normalized dust concentrations for individual tests, as well as the averages of the three normalized concentrations for each test condition. A summary of these average normalized gravimetric concentrations for each sampling location and test condition is provided in table 2. All subsequent data analysis utilized normalized dust concentrations.

The average dust concentrations in table 2 represent a wide range of dust levels for the various conditions tested, indicating that the test parameters had a substantial impact on resulting dust levels. Since differences were observed from one sampling location to another, each sampling location will be evaluated on an individual basis.

The relative effectiveness of each control parameter was examined by comparing the average dust level with all parameters at baseline levels (15 gpm, 80 psi, and 3,000 cfm) to the average dust level with one parameter raised to its highest level (15 gpm, 80 psi, and 9,000 cfm). Airflow was the parameter resulting in the greatest reductions. At the operator and return locations, reductions of 99% and 57%, respectively, were observed.

To obtain an indication of the statistical significance of the three test parameters, analysis of variance (ANOVA) was conducted with a statistical software package. Table 3 contains a summary of the ANOVA results. The calculated F* (variance ratio) statistics show that the main effects are statistically significant for each test location. Also, the individual effects of the test parameters are statistically significant in nearly every case. An indication of the relative variation explained by each of the test parameters is provided by the "sum of squares" data, where a larger value for a control parameter signifies that the parameter explains more of the variation in the dependent variable. Examination of the sum of squares indicates that airflow typically has the most significant impact.

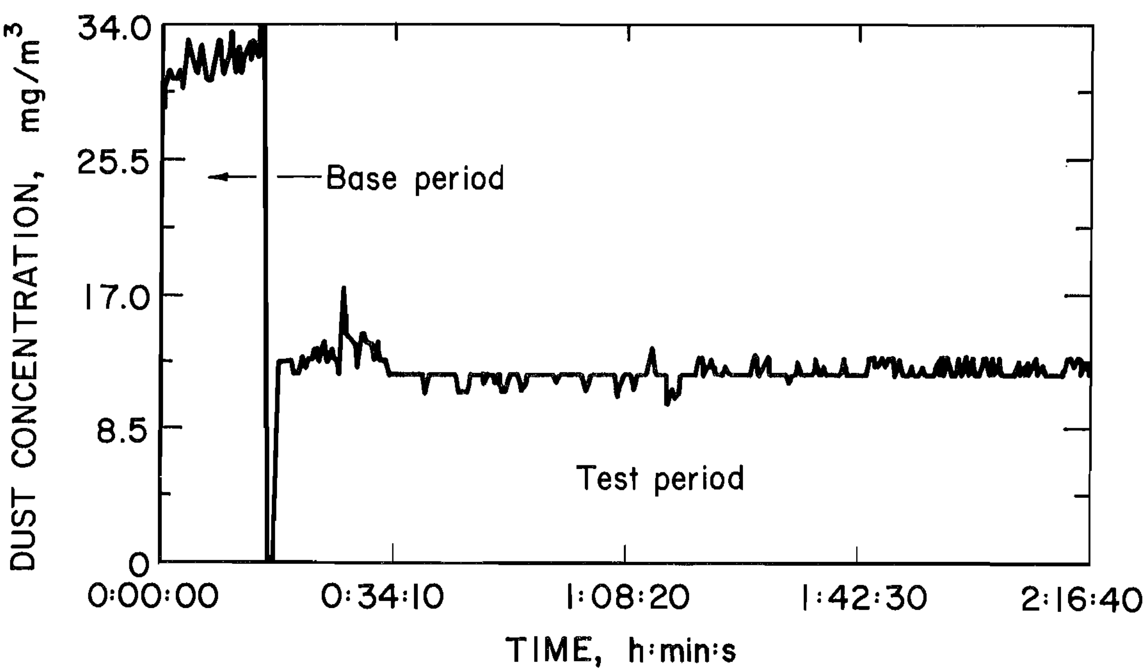

Figure 4.—Typical RAM output from a test.

Table 2.—Summary of average gravimetric dust concentrations

Waterflow, gpm	Water pressure, psi	Airflow, cfm	Average dust concentration, mg/m³			
			Operator		Return	
			Box cut	Slab cut	Box cut	Slab cut
15	80	3,000	8.20	2.25	27.7	20.1
15	80	9,000	.23	.02	11.8	11.6
15	140	6,000	.63	1.88	12.2	13.0
15	200	3,000	6.03	6.12	14.6	13.7
15	200	9,000	.06	.02	7.2	10.7
25	80	6,000	.22	1.27	14.3	14.6
25	140	3,000	2.65	3.11	14.6	14.1
25	140	6,000	.30	.38	11.0	11.5
25	140	9,000	.14	.02	8.2	9.8
25	200	6,000	.50	.60	10.7	9.8
35	80	3,000	7.76	2.38	18.6	17.0
35	80	9,000	.13	.05	8.9	11.3
35	140	6,000	.47	.38	10.5	9.4
35	200	3,000	4.79	.69	11.6	8.8
35	200	9,000	.25	.30	8.0	7.2

Table 3.—Summary of ANOVA results

Sampling location and source of variation	Sum of squares	Variance ratio (F*)
OPERATOR LOCATION		
Box cut:		
Main effects	356.8	43.8
Waterflow (gpm)	7.9	2.9
Water pressure (psi) ..	11.6	4.3
Airflow (cfm)	271.1	99.8
Residual	59.7	NAp
Slab cut:		
Main effects	80.7	9.3
Waterflow (gpm)	13.0	4.5
Water pressure (psi) ..	.9	.3
Airflow (cfm)	63.2	22.0
Residual	63.3	NAp
RETURN LOCATION		
Box cut:		
Main effects	946.2	21.1
Waterflow (gpm)	77.8	5.2
Water pressure (psi) ..	277.3	18.6
Airflow (cfm)	555.6	37.2
Residual	328.2	NAp
Slab cut:		
Main effects	424.4	23.5
Waterflow (gpm)	71.2	11.8
Water pressure (psi) ..	185.1	30.7
Airflow (cfm)	162.4	27.0
Residual	132.6	NAp

NAp Not applicable.

NOTE.—Criteria for waterflow, water pressure, and airflow:

Hypothesis: Ho: all $\alpha_i = 0$ (parameter not significant).

Ha: not all $\alpha_i = 0$ (parameter is significant).

Decision rule: If $F^* < F_{(0.95;\, a-1,(n-1)abc)}$, conclude Ho.

If $F^* > F_{(0.95;\, a-1,(n-1)abc)}$, conclude Ha.

$F_{(0.95;\, 2,54)} = 3.18.$

To illustrate the significance of a control parameter, figure 5 contains the mean dust levels in the box cut at the return sampling location obtained at each level of airflow, independent of water levels. This figure also contains 95% confidence intervals for each of these means. All intervals are mutually exclusive, indicating that a significant difference exists at the 95% confidence level between dust concentrations observed for different levels of airflow.

Conversely, figure 6 contains the mean dust levels and 95% confidence intervals obtained for waterflow test levels. These data indicate that a significant difference exists between the 15- and 25-gpm test conditions, but not between 25- and 35-gpm levels. This suggests that increasing test waterflow from 15 to 25 gpm significantly reduced dust levels, but an additional increase to 35 gpm did not result in significantly improved dust levels.

The ANOVA analysis simply determines if significant differences exist, but does not attempt to define the relationship between the test parameters and dust levels. Multiple regression was used to define this relationship.

Because curvature effects were suspected and interactions between the test parameters were likely, a second-order polynomial was fitted to the data. Often when fitting a polynomial to data, a high correlation between the linear and squared terms exists and can cause computational difficulties.[6] A check of the correlation between these terms confirmed a high correlation. As a result, a data transformation for the independent variables was made. The difference between each individual test value and the mean value for that test parameter was used as transformed input data for the regression analysis. For example, rather than using 15, 25, or 35 gpm as an input for the waterflow variable, the data were transformed as described (i.e., 15 - 25 = -10), and -10, 0, or 10 were used as input. This transformation substantially reduced the correlation between the terms used in the polynomial model. Also, to have all parameters relatively equal in magnitude, the airflow data were rescaled to a range of 30 to 90 rather than 3,000 to 9,000.

The response surface for the second-order model with three independent variables is defined as

$$E[Y] = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2,$$

where $E[Y]$ = expected value of response variable,

b_i = regression coefficient,

and x_i = independent variable.

[6]Neter, J., W. Wasserman, and M. H. Kutner. Applied Linear Statistical Models. Irwin, 1985, pp. 300-317.

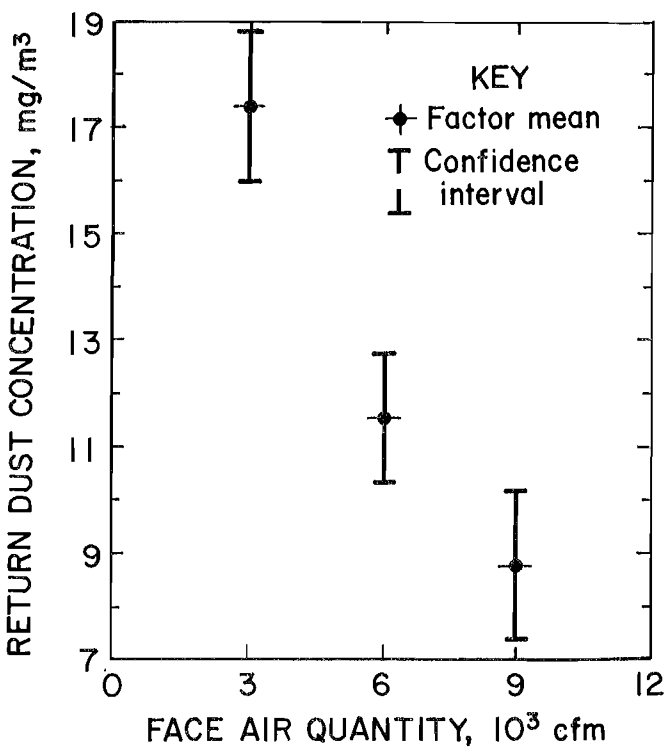

Figure 5.—ANOVA mean and 95% confidence intervals for main effect of airflow in box cut.

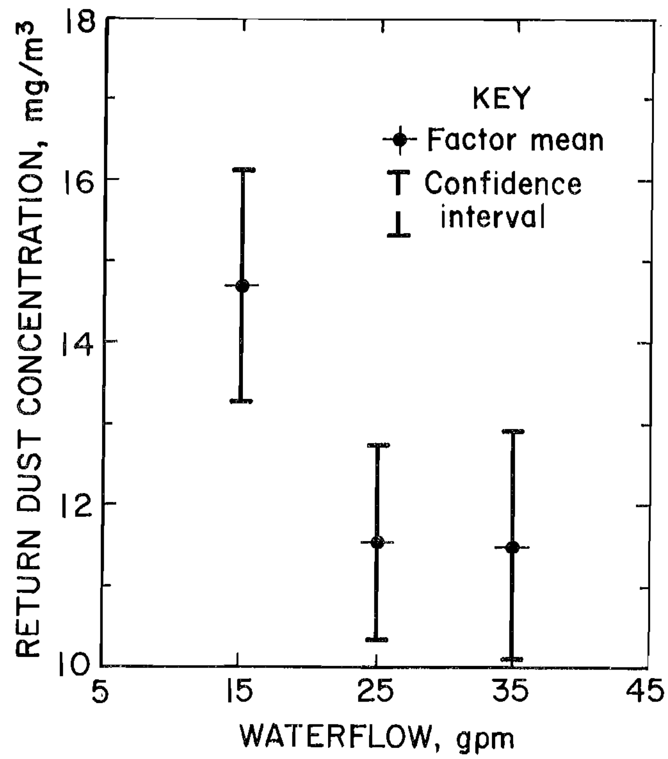

Figure 6.—ANOVA mean and 95% confidence intervals for main effect of waterflow in box cut.

For our purposes, E[Y] would represent expected dust concentration, while x_1, x_2, and x_3 would represent waterflow, water pressure, and airflow, respectively. Typically, when fitting polynomial expressions, the full model may not be needed, and those terms that are not significant can be excluded from the model. For each sampling location, the normalized dust concentrations from each test were entered into a statistical computer package. A stepwise regression procedure then determined which terms were significant for each sampling location. Table B-5 contains the variable terms found to be significant, along with the related variable coefficients, standard error values, t-values, and the significance levels from the regression analysis. The following equations and corresponding adjusted coefficients of multiple determination (R^2_a) were obtained:

Operator position:

Box cut: $$Y = -0.15284 - 0.00858p - 0.09663c + 0.00035pc + 0.00897g^2 + 0.00023p^2 + 0.000213c^2$$

$$(R^2_a = 0.87)$$

Slab cut: $$Y = 0.72260 - 0.06843g - 0.04694c - 0.00112gp + 0.00231gc + 0.00087c^2$$

$$(R^2_a = 0.68)$$

Return position:

Box cut: $$Y = 11.20004 - 0.16987g - 0.04729p - 0.14346c + 0.00218gp + 0.00481gc + 0.00102pc + 0.00058p^2$$

$$(R^2_a = 0.85)$$

Slab cut: $$Y = 11.42310 - 0.16704g - 0.04063p - 0.07635c - 0.00098gp + 0.00191gc + 0.00064pc + 0.00031p^2$$

$$(R^2_a = 0.84),$$

where Y = dust level, mg/m^3,

g = water flow, -10 to 10 gpm,

p = water pressure, -60 to 60 psi,

and c = airflow, -30 to 30 cfm × 100.

These equations indicate that not all parameters are significant for each sampling location. However, all of the equations do contain interaction and quadratic terms.

The coefficient of multiple determination (R^2) is an indication of the proportionate reduction of the total variation in Y that is explained by the independent variables that are included in the model. A value of 1.0 would indicate that a perfect correlation exists and that all observations fall directly on the fitted response surface. The R^2_a utilizes the number of independent variables in the model in its calculation and provides a more realistic measure of the value gained from adding variables to a model. All sampling locations except the operator position in the slab cut had an R^2_a greater than or equal to 0.84, indicating that at least 84% of the variation in the observed dust levels is explained by the independent variables included in each model. The data from the operator location in the slab cut appeared more variable, thus a lower R^2_a could be expected.

After each model was developed, analysis of the residuals was conducted to determine if the model was a valid representation. Graphical analysis of the residuals indicated that the developed models were appropriate.

The models were then converted into the forms needed to accept the original control parameter levels. This conversion resulted in the following:

Operator position:

Box cut: $$Y = 27.48569 - 0.4485g - 0.09282p - 0.40119c + 0.00035pc + 0.00897g^2 + 0.00023p^2 + 0.00213c^2,$$

Slab cut: $$Y = 7.92744 - 0.05055g + 0.02798p - 0.20892c - 0.00112gp + 0.00231gc + 0.00087c^2,$$

Return position:

Box cut: $$Y = 65.44306 - 0.76405g - 0.32497p - 0.40689c + 0.00218gp + 0.00481gc + 0.00102pc + 0.00058p^2,$$

Slab cut: $$Y = 36.73387 - 0.14400g - 0.14109p - 0.21372c - 0.00098gp + 0.00191gc + 0.00064pc + 0.00031p^2,$$

where Y = dust level, mg/m^3,

g = water flow, 15 to 35 gpm,

p = water pressure, 80 to 200 psi,

c = airflow, 30 to 90 cfm × 100.

These equations were used to construct response surface plots and contour plots for each sampling location. The results obtained for each location are presented and discussed below.

PREDICTED DUST LEVELS AT OPERATOR POSITION

Figure 7 shows the response surface plot from the operator model for the box cut, with waterflow held constant at 15 gpm. This plot illustrates the impact of increasing airflow and water pressure and shows the curvature that is present in the relationship. As illustrated, increases in air quantity result in reduced dust levels until airflow exceeds 8,000 cfm. Increasing the water pressure results in reduced dust levels to only about 140 psi, after which the dust levels begin to rise. These increases in dust levels probably result from undesirable airflow turbulence created by high airflow and additional rollback caused by the higher water pressures.[7] The point at which additional increases in dust control parameters no longer result in corresponding decreases in dust concentration is referred to as the "point of diminishing return." The point of diminishing return should be identified to minimize air and water usage while maximizing dust control.

Filters with dust weights below the capabilities of the weighing balance were found for some of the higher airflow conditions, resulting in average dust concentrations as low as 0.02 mg/m^3 (table 2). The inclusion of these values as input for the multiple regression analysis caused some of the model-predicted dust levels for high airflows to be negative. Realistically, negative dust levels cannot occur, but were reported in this case to illustrate trends.

To more readily identify the point of diminishing return, contour plots were produced. Figure 8 contains the contour plot for the operator position in the box cut at a constant waterflow of 15 gpm. Minimum dust levels can be identified for different conditions. For example, near 7,000 cfm, the dust levels decrease until approximately 140 psi is reached, then the dust levels remain constant before increasing. However, near 3,000 cfm, the dust levels continue to decrease until approximately 170 psi is reached. The interaction between water pressure and airflow accounts for the shift in effectiveness at different water pressures. Similarly, with increasing airflow, dust levels continue to decrease until approximately 8,400 cfm

[7]Ruggieri, S. K., T. L. Muldoon, C. Babbitt, and E. Lee. Improved Diffuser and Sprayfan Systems for Ventilation of Coal Mine Working Faces (contract J0113010, Foster-Miller, Inc.). BuMines OFR 18-86, 1985, pp. 12-124; NTIS PB 86-168440.

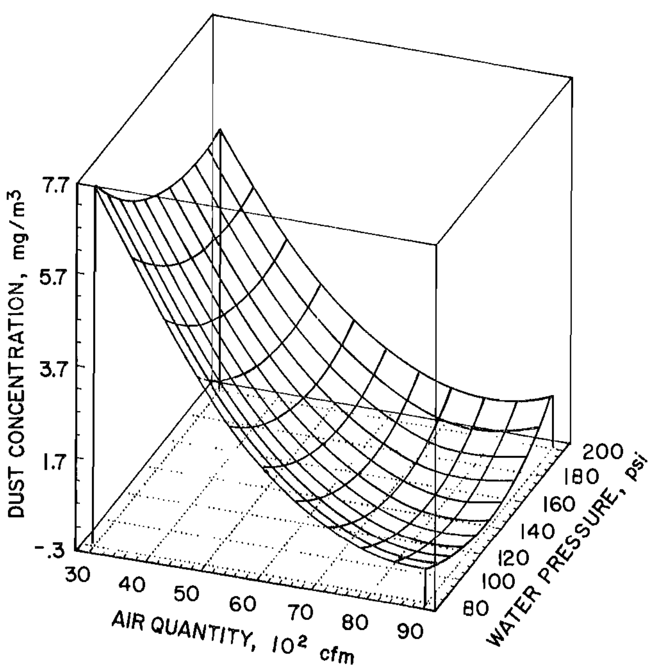

Figure 7.—Response surface plot of predicted operator dust levels in box cut at 15-gpm waterflow.

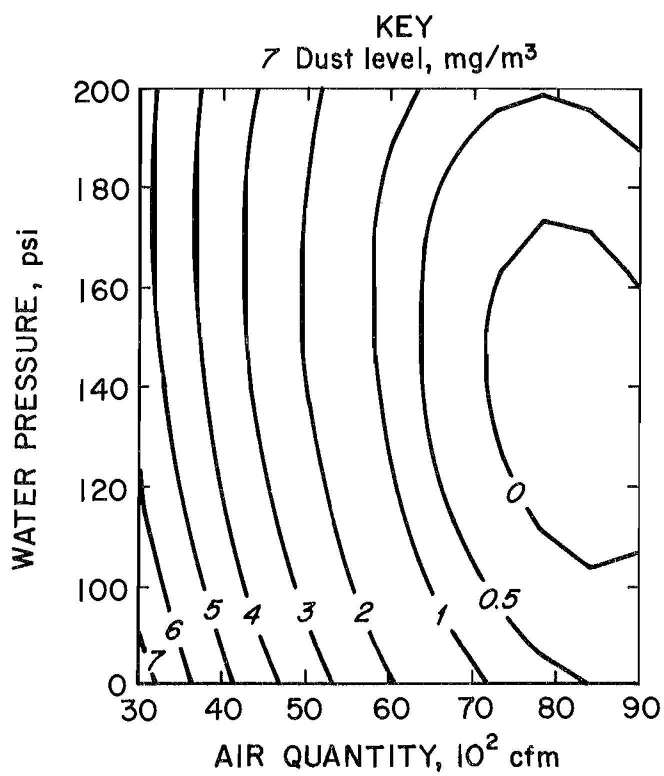

Figure 8.—Contour plot of predicted operator dust levels in box cut at 15-gpm waterflow.

is reached. Apparently, at higher air quantities, undesirable airflow pattern may be forming to carry dust back toward the operator. Similar dust contours were found for higher waterflow conditions (figs. 9-10).

Contour plots were constructed with the water pressure held constant to determine the impact of waterflow on dust levels. Figure 11 illustrates the dust levels found in the box cut with pressure held constant at 80 psi. The patterns present in this figure are quite similar to those found for constant water flow. In this case, application of approximately 25-gpm waterflow resulted in minimized dust levels. As a result, for the box cut location, one could limit the use of water to approximately 25 gpm and 140 psi without sacrificing dust control for the system tested. Increases in airflow up to 8,400 cfm would result in improvements in dust exposure of the operator.

The effect of control parameter interaction was much more pronounced for the operator position in the slab cut. Figures 12 through 14 provide the response surface plots for constant waterflow rates of 15, 25, and 35 gpm, respectively. These plots show how the surface representing predicted dust levels completely reverses for different water pressure-waterflow combinations. Increases in water pressure result in increases in dust at 15-gpm waterflow, no impact on dust at 25-gpm waterflow, and reductions in dust at 35-gpm waterflow.

The dust levels observed at the operator position in the slab cut over the range for airflow are also somewhat different from that found in the box cut. Increases in airflow resulted in reductions in dust levels in all cases except when 35-gpm waterflow was used. As shown in the contour plot (fig. 15), additional increases in the air quantity aggravated operator dust levels after reaching approximately 7,200 cfm.

For the slab cut, the operator's cab was positioned closer to the corner of the crosscut, where less consistent airflow patterns are more likely to be encountered. Also, the width of the slab cut resulted in approximately half of the water sprays impacting against the face, while the other sprays discharged into the open area of the box cut. Thus, face airflow patterns different from those present in the box cut were expected. These factors contributed to varying face airflow patterns and turbulence that affected the dust levels at the operator's position.

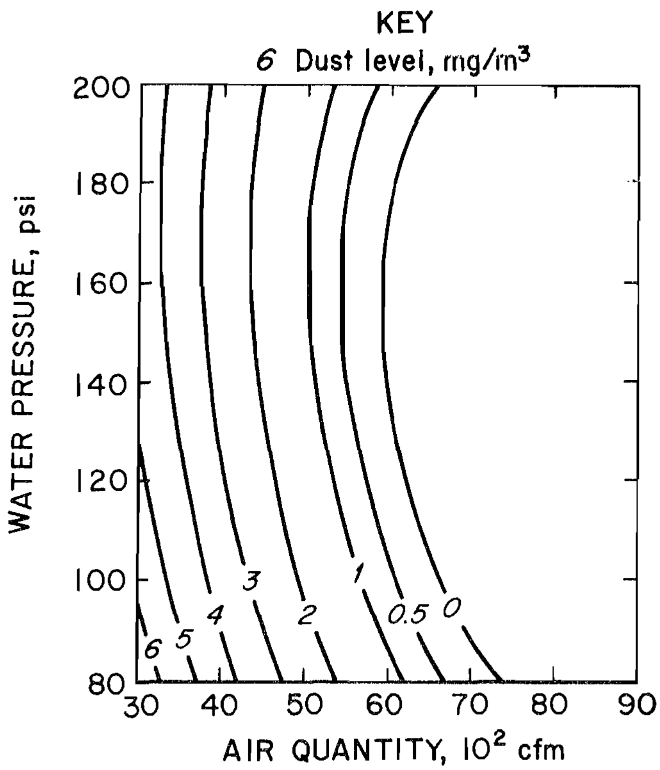

Figure 9.—Contour plot of predicted operator dust levels in box cut at 25-gpm waterflow.

Owing to the interaction taking place, a unique point of diminishing return was not found for the operator position in the slab cut. For each level of waterflow, a different combination of control parameters resulted in the lowest dust levels. Table 4 provides a summary of the predicted dust concentrations calculated for both the slab and box cuts for the low-, middle-, and high-level combinations of the control parameters. These data offer insight into optimum combinations at various levels of the different control parameters.

Table 4.—Summary of predicted dust concentrations for operator sampling location, milligrams per cubic meter

	15 gpm			25 gpm			35 gpm		
	80 psi	140 psi	200 psi	80 psi	140 psi	200 psi	80 psi	140 psi	200 psi
BOX CUT									
3,000 cfm . .	7.52	5.56	5.21	6.62	4.66	4.32	7.52	5.56	5.21
6,000 cfm . .	2.07	.74	1.04	1.17	-.15	.14	2.07	.74	1.04
9,000 cfm . .	.44	-.24	.69	-.45	-1.14	-.21	.44	-.24	.69
SLAB CUT									
3,000 cfm . .	3.62	4.29	4.96	2.91	2.91	2.91	2.21	1.53	0.86
6,000 cfm . .	.74	1.41	2.08	.72	.72	.72	.71	.04	-.63
9,000 cfm . .	-.59	.09	.76	.10	.10	.10	.78	.11	-.57

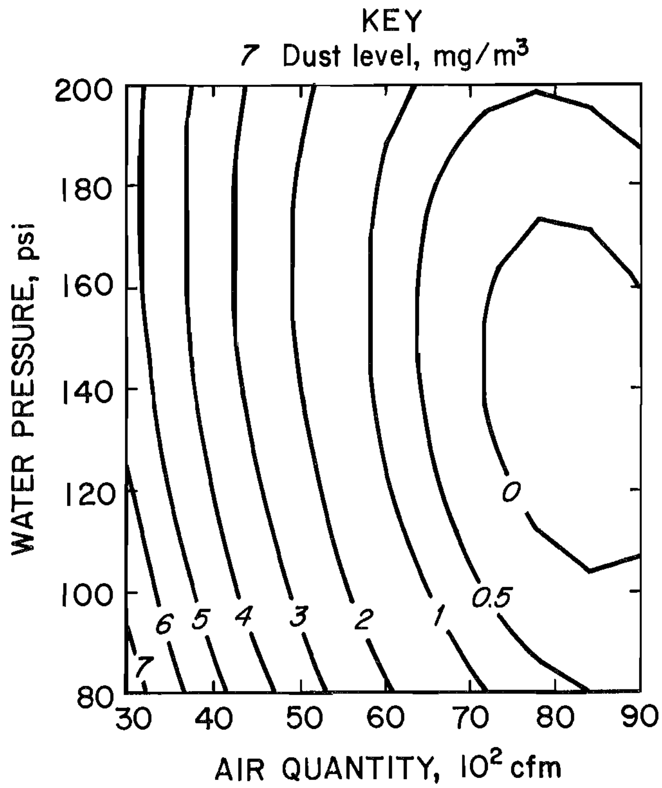

Figure 10.—Contour plot of predicted operator dust levels in box cut at 35-gpm waterflow.

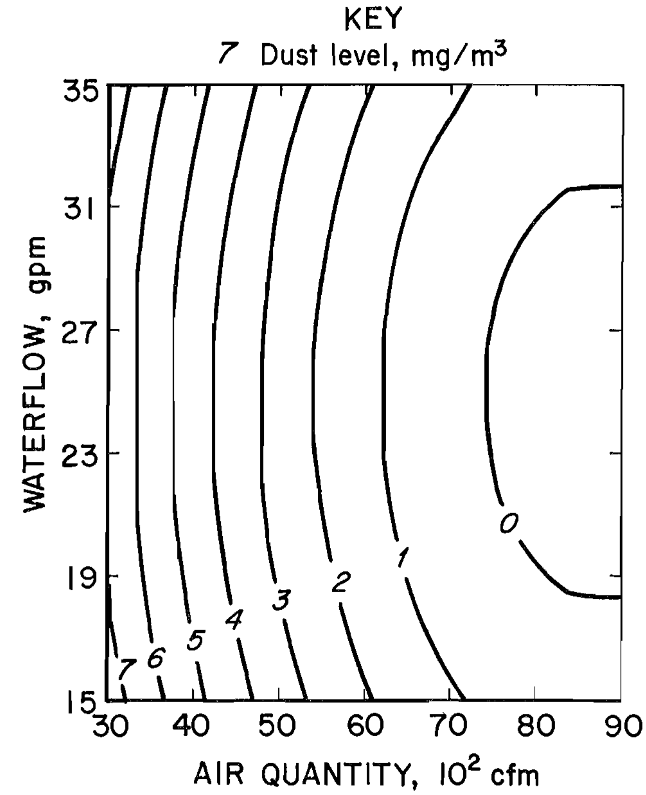

Figure 11.—Contour plot of predicted operator dust levels in box cut at 80-psi water pressure.

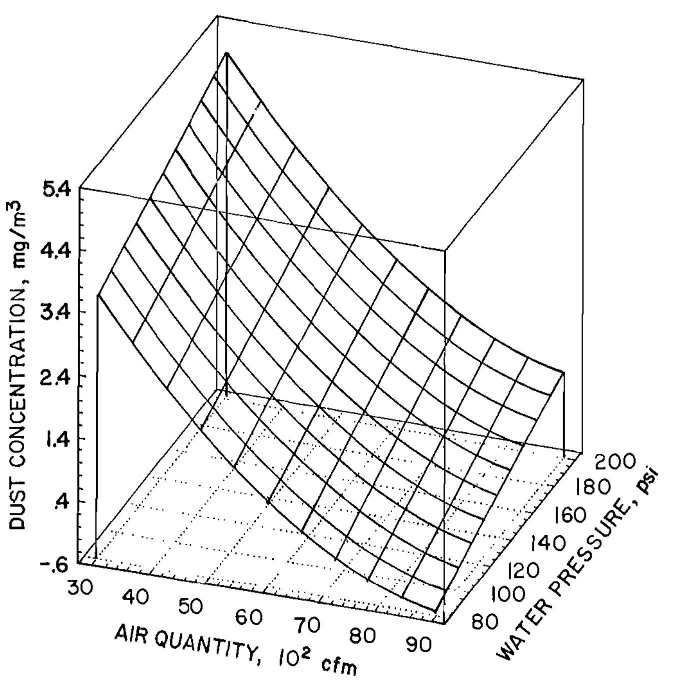

Figure 12.—Response surface plot of predicted operator dust levels in slab cut at 15-gpm waterflow.

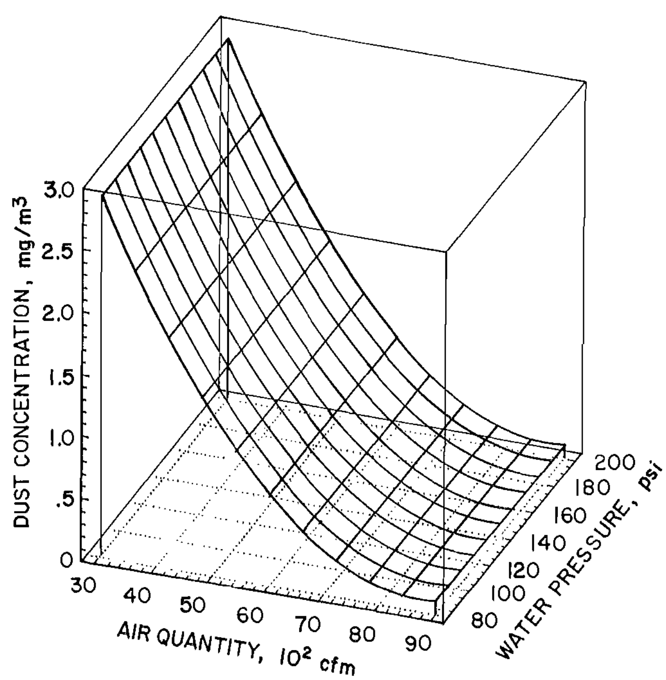

Figure 13.—Response surface plot of predicted operator dust levels in slab cut at 25-gpm waterflow.

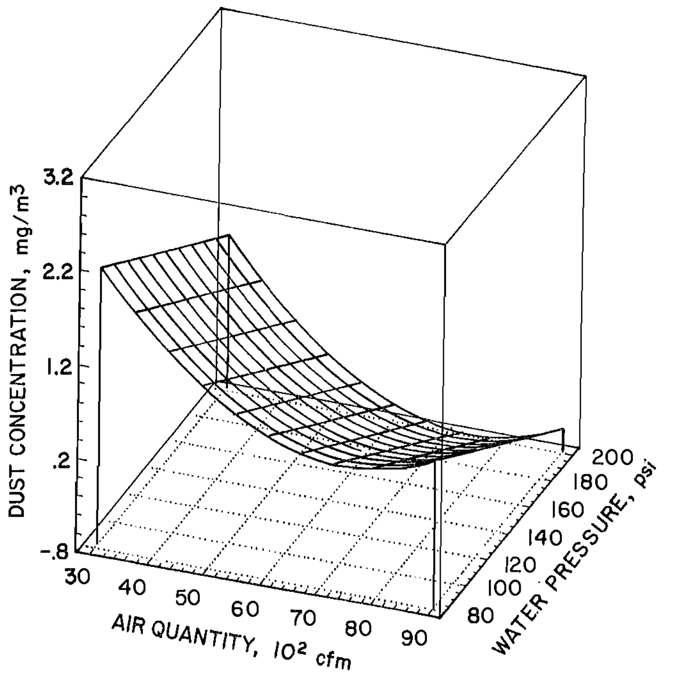

Figure 14.—Response surface plot of predicted operator dust levels in slab cut at 35-gpm waterflow.

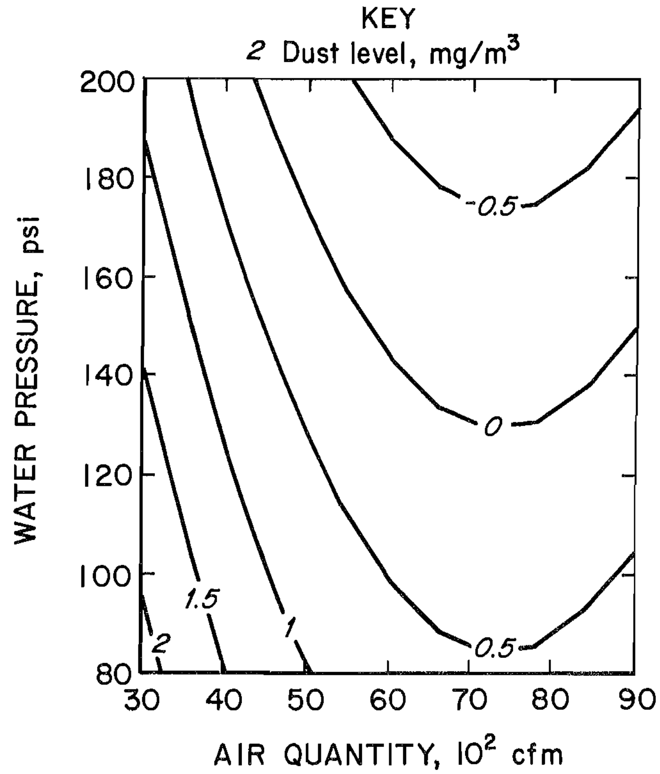

Figure 15.—Contour plot of predicted operator dust levels in slab cut at 35-gpm waterflow.

PREDICTED DUST LEVELS IN RETURN POSITION

The dust reductions found for the return sampling position generally followed a more consistent trend for both the box and slab cut locations, particularly at lower waterflows. Figures 16 and 17 show the response surface plots for the box and slab cuts at a constant waterflow of 15 gpm. Although the magnitude of the dust levels differs, the shape of each response surface is similar. Examination of the contour plots (figs. 18-19) further confirm that similar dust trends are found for both cuts.

Return dust concentrations predicted by the regression models are provided in table 5. These data indicate that airflow is the most significant of the individual control parameters. Increases in airflow resulted in decreases in dust levels throughout the range tested, with a maximum reduction of 57% in the box cut when dust levels at 3,000 cfm are compared with those at 9,000 cfm.

Table 5.—Summary of predicted dust concentrations for return sampling location, milligrams per cubic meter

	15 gpm			25 gpm			35 gpm		
	80 psi	140 psi	200 psi	80 psi	140 psi	200 psi	80 psi	140 psi	200 psi
				BOX CUT					
3,000 cfm . .	26.71	18.65	14.74	22.26	15.50	12.91	17.81	12.36	11.07
6,000 cfm . .	19.13	12.90	10.83	16.12	11.20	10.44	13.11	9.50	10.05
9,000 cfm . .	11.54	7.15	6.93	9.97	6.90	7.98	8.41	6.64	9.03
				SLAB CUT					
3,000 cfm . .	20.07	15.96	14.06	18.42	13.71	11.23	16.76	11.47	8.40
6,000 cfm . .	16.06	13.09	12.36	14.97	11.42	10.10	13.89	9.75	7.84
9,000 cfm . .	12.04	10.23	10.65	11.53	9.13	8.96	11.02	8.03	7.27

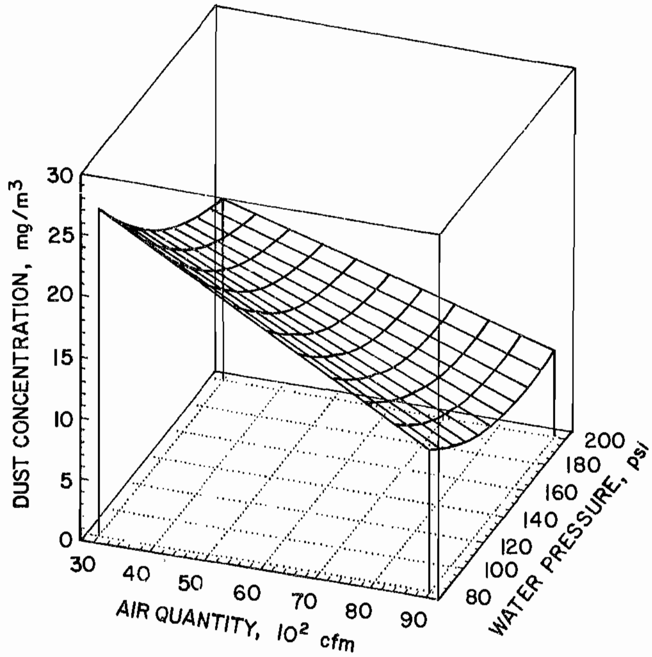

Figure 16.—Response surface plot of predicted return dust levels in box cut at 15-gpm waterflow.

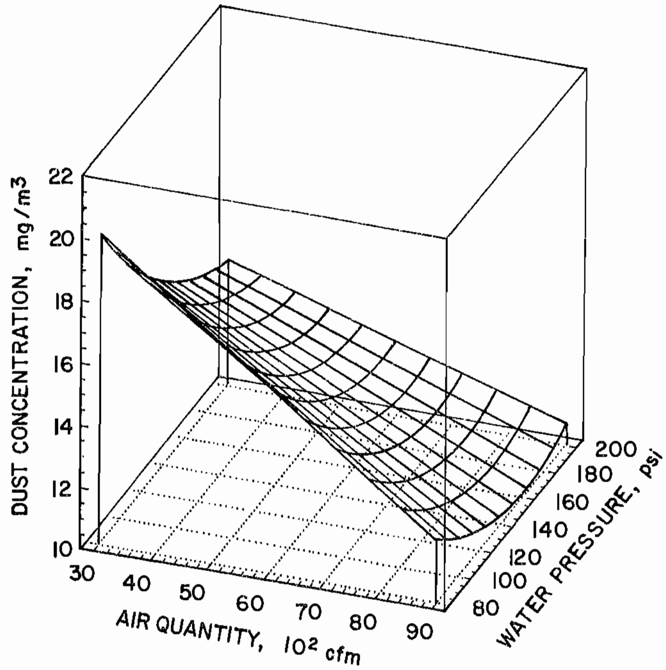

Figure 17.—Response surface plot of predicted return dust levels in slab cut at 15-gpm waterflow.

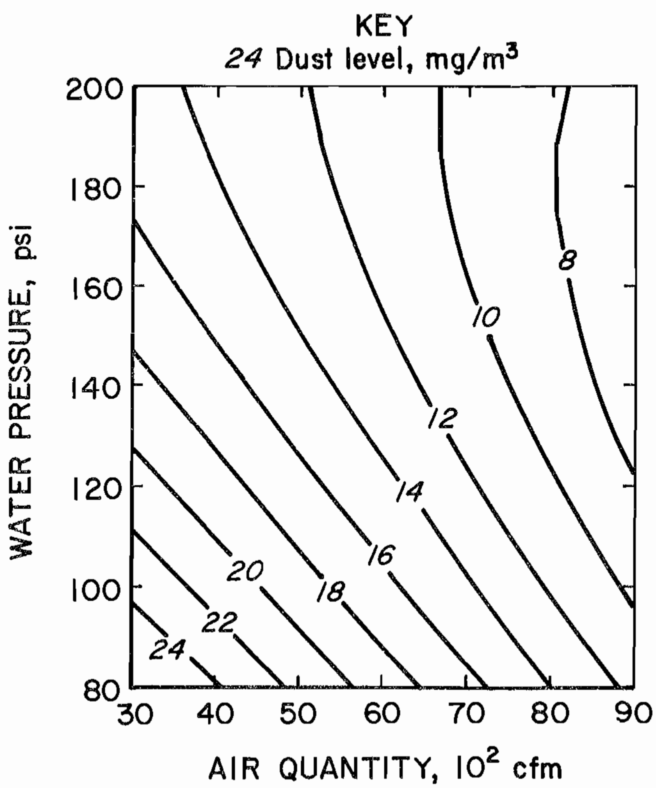

Figure 18.—Contour plot of predicted return dust levels in box cut at 15-gpm waterflow.

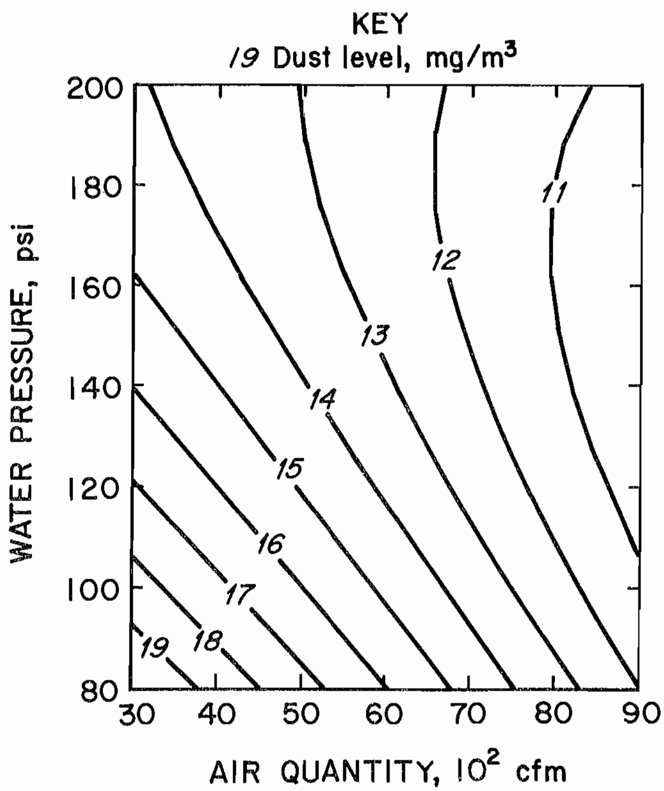

Figure 19.—Contour plot of predicted return dust levels in slab cut at 15-gpm waterflow.

The continued improvement achieved with airflow in the return location, as compared with airflow in the operator position, is due to the method by which airflow improves dust control at each location. At the return location, improvements in dust levels are a result of increased dilution of the dust cloud. At the operator's position, increased airflow also offers greater dilution, but the primary dust control appears to come from the prevention of rollback. As evidenced in the operator data, rollback is a factor that can aggravate operator dust exposure.

For the 15-gpm condition, water pressure interaction with air quantity was present so that the point of diminishing return was not constant. At lower air quantities, higher water pressures continued to be effective, but as the air quantity was raised, increases in water pressure became ineffective. For example, at 3,000 cfm, dust reductions were realized over the 80- to 200-psi range, but at 8,000 cfm, reductions in dust levels ceased at approximately 150 psi.

Similar conditions were also observed for the higher waterflow conditions (figs. 20-21). At low airflows, higher water pressures typically continued to be effective, but as the airflow increased, the effectiveness of increasing water pressure was diminished.

Figures 22 and 23 show the response surface plots for the box and slab cuts with the water pressure held constant at 80 psi. These plots show that increased waterflow reduces dust levels, but not at a very significant rate, particularly when compared with the improvement made by increasing airflow. These plots reinforce the finding that airflow has the most significant impact on dust levels and that less dramatic changes are realized with waterflow.

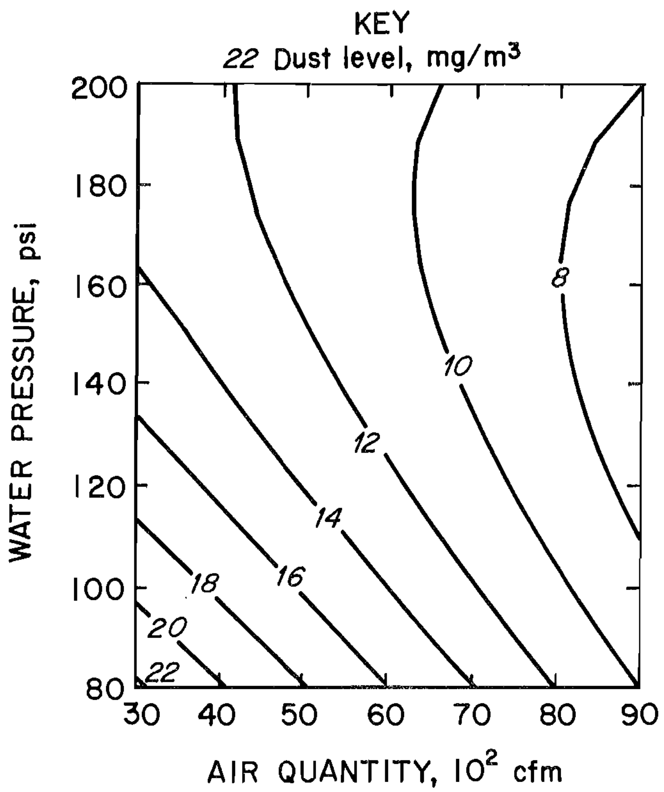

Figure 20.—Contour plot of predicted return dust levels in box cut at 25-gpm waterflow.

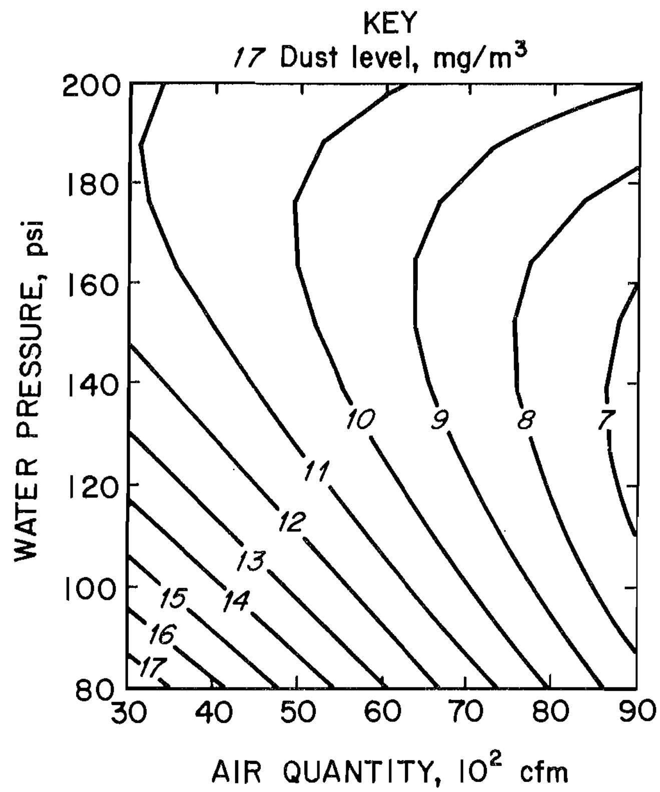

Figure 21.—Contour plot of predicted return dust levels in box cut at 35-gpm waterflow.

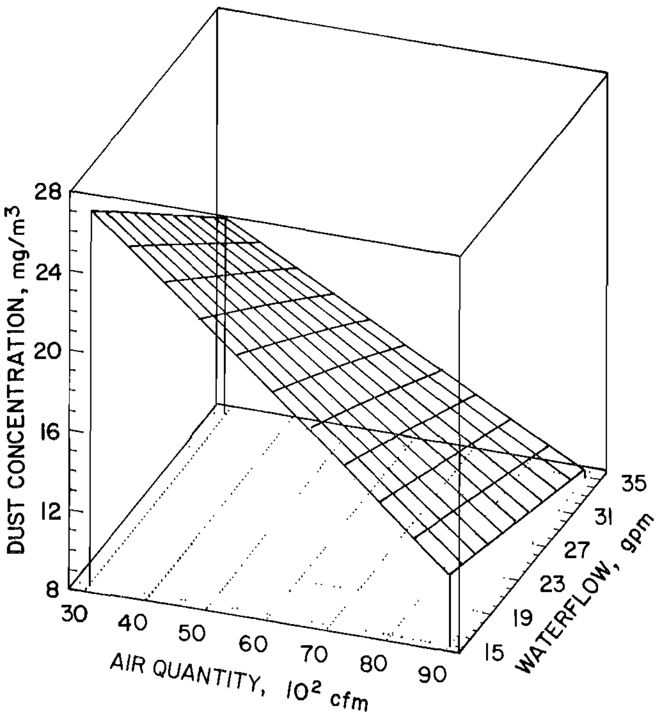

Figure 22.—Response surface plot of predicted return dust levels in box cut at 80-psi water pressure.

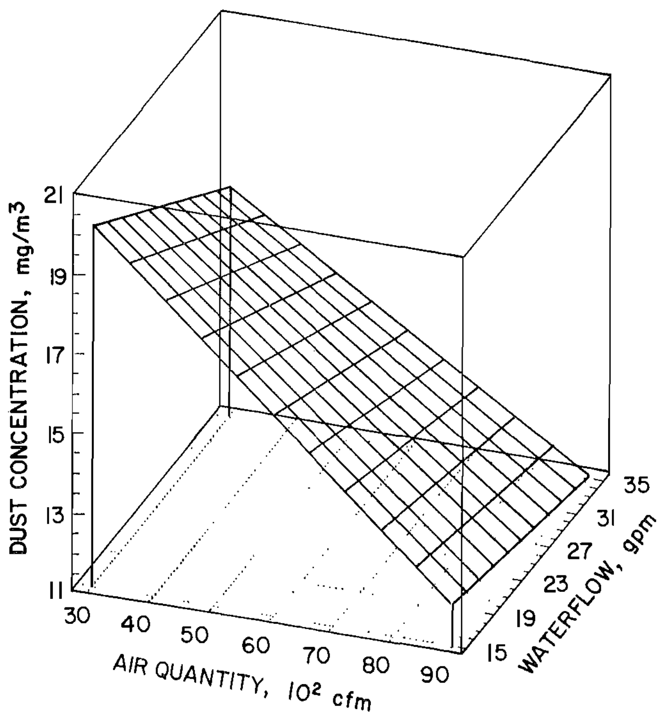

Figure 23.—Response surface plot of predicted return dust levels in slab cut at 80-psi water pressure.

CONCLUSIONS

Results of these tests show that airflow has the potential to make the most substantial improvement in dust control at both the operator and return locations. Reductions of 57% in the return and 99% in the operator position were observed. These reductions were attributed to the overall dilution of the dust cloud and/or the prevention of rollback at the operator location. However, the possibility of aggravating operator dust exposure was also observed for certain higher airflow conditions. For example, above 8,400 cfm in the box cut, counterproductive airflow patterns apparently developed and increased operator dust levels.

Water pressure was shown to have a significant impact on dust levels, particularly at the operator's position. Initially, increases in water pressure above base conditions reduced dust concentrations, but when the water pressure reached higher levels, dust rollback was observed. The potential for aggravating operator dust levels occurred only at nozzle pressures above 140 psi. Consequently, on-site testing is recommended when water pressures above 140 psi are utilized.

Water quantity was the control parameter having the least impact when operator and return dust levels were considered. Generally, increases above 25 gpm offered little improvement in dust control. However, the test setup did not account for another factor—coal transport—where increased waterflow could have additional benefits. No provisions were available to simulate the dust liberation that could occur from coal transfer from the miner conveyor into a shuttle car. Any dust generated by this operation has the potential to be carried to the miner operator's location. In this situation, it could be surmised that increased water application during cutting may reduce the dust liberation during transfer as a result of a wetter coal product.

Interaction between control parameters was prevalent throughout the test series. Often, interactions caused the point of diminishing return for one control parameter to be dependent on the level of another control parameter. With such interaction present, the level of application for two of the three parameters tested must be known to determine the desired level of the third parameter. In light of these interactions, the calculated regression models would be useful in selecting possible alternatives for reducing dust levels at the operator and return locations. As such, appendix A contains a computer program, written in GW-BASIC, that can be utilized to calculate predicted dust levels for different air-water combinations.

Results also confirmed that application of control parameters at particular levels may significantly benefit one sampling location (return), but adversely impact another location (miner operator). The objective of the mine operator must be considered when selecting application levels for these dust control parameters. If a mine has personnel working downstream of the miner, one set of control parameters may be more suitable than that selected for a mine that has the miner operator out of compliance.

It is apparent that application of airflow and waterflow is not a straightforward undertaking. For mining conditions simulated by this laboratory testing, increases in airflow to 8,400 cfm, in water pressure to 140 psi, and in water quantity to 25 gpm offered improvements in dust control at the operator and return locations. However, in-mine testing should be the final guide for determining optimum conditions for an individual continuous miner operation.

APPENDIX A.—DUSTCALC PROGRAM

As previously stated, the calculated regression models can assist mine operators in their selection of application levels for the dust control parameters examined in this laboratory study. To facilitate this effort, a program was written in Microsoft GW-BASIC version 3.23 for use on a personal computer to calculate predicted dust levels for user-specified combinations of the control parameters. These dust levels represent dust generation during mining and do not include machine downtimes or other non-production times. The input range for the control parameters is restricted to the maximum and minimum levels used during testing, as the validity of the models outside of this range is uncertain.

The program prompts the user for the desired control levels to examine, then calculates the expected dust levels at the operator and return locations. This program utilizes the regression models developed from the box cut data. Combinations of various levels for the control parameters can be examined to identify dust trends in seeking optimum conditions.

The program code follows and should be entered into a GW-BASIC program. For each program statement (i.e., 10, 20, 30...), enter all of the code for that statement before entering a carriage return. Some statements may exceed the screen width and automatically wrap to the next line, but this will not cause problems. After entering the code, the program should be saved before being compiled and executed.

CODE FOR DUSTCALC PROGRAM

```
10 CLS
20 PRINT "                    DISCLAIMER"
30 PRINT
40 PRINT "The Bureau of Mines expressly declares that there are no warranties,"
50 PRINT "express or implied, which apply to the software contained herein."
60 PRINT "By acceptance and use of said software, which is conveyed to the "
70 PRINT "user without consideration by the Bureau of Mines, the user hereof"
80 PRINT "expressly waives any and all claims for damage and/or suits for or"
90 PRINT "by reason of personal injury, or property damage, including special"
100 PRINT "consequential, or other similar damages arising out of or in any way"
110 PRINT "connected with the use of the software contained herein."
120 PRINT
130 PRINT
140 PRINT
150 INPUT "                    Hit return to continue.", A
160 CLS
170 PRINT "               PRIMARY DUST CONTROLS FOR CONTINUOUS MINERS"
180 PRINT
190 PRINT "This program uses data generated from laboratory tests conducted"
200 PRINT "by the U.S. Bureau of Mines to predict dust levels for continuous"
210 PRINT "miners equipped with hollow cone sprays oriented perpendicular to the"
220 PRINT "face. These predicted dust levels are relative values representing"
230 PRINT "dust generated during mining only. These dust levels should not be"
240 PRINT "considered absolute or representative of full-shift concentrations,"
250 PRINT "but can be used to identify areas of potential dust control improve-"
260 PRINT "ment by simulating changes in the control parameters."
270 PRINT
280 INPUT "Which parameter would you like to examine? (1=gpm 2=psi 3=cfm 4=quit) ",E
290 PRINT
300 ON E GOTO 320,700,1080,1500
310 IF E<1 OR E>4 THEN PRINT "Invalid entry, try again...": GOTO 280
320 INPUT "How many levels of water flow are you interested in?
     (1-4) ",N
330 IF N<1 OR N>4 THEN PRINT " Invalid entry, try again...": GOTO 320
```

```
340 FOR I=1 TO N
350 INPUT "Enter a water flow rate to evaluate (15-35 gpm)", G(I)
360 IF G(I)<15 OR G(I)>35 THEN PRINT "Invalid entry, try again...": GOTO 350
370 NEXT
380 PRINT
390 INPUT "Enter your average spray pressure (80-200 psi) ",P
400 IF P<80 OR P>200 THEN PRINT "Invalid entry, try again...": GOTO 390
410 INPUT "Enter your average face airflow (3000-9000 cfm)  ",CFM
420 IF CFM<3000 OR CFM>9000 THEN PRINT "Invalid entry, try again...": GOTO 410
430 C=CFM/100
440 PRINT
450 FOR I=1 TO N
460 OP(I) = 28.75 - .4485*G(I) - .092816*P - .401194*C + .000354*P*C + .00897*G(I)^2 + .000225*P^2 + .002125*C^2
470 RT(I) = 65.44306 - .764053*G(I) - .324973*P - .406892*C + .002181*G(I)*P + .004814*G(I)*C + .001022*P*C
    + .000578*P^2
480 NEXT
490 PRINT "Predicted dust levels in mg/m3 at "P" psi and "CFM" cfm:"
500 PRINT
510 PRINT "Water Flow","Operator","Return"
520 FOR I=1 TO N
530 G$=" gpm"
540 PRINT USING "###&        ##.##        ##.##";
    G(I),G$,OP(I),RT(I)
550 NEXT
560 PRINT
570 INPUT "Would you like these results printed? (1=yes 2=no) ",PR
580 IF PR=2, GOTO 1450
590 IF PR<1 OR PR>2 THEN PRINT "   Invalid entry, try again...": GOTO 570
600 LPRINT "Predicted dust levels in mg/m3 at "P" psi and "CFM" cfm:"
610 LPRINT
620 LPRINT "Water Flow","Operator","Return"
630 FOR I=1 TO N
640 LPRINT USING "###&        ##.##        ##.##";
    G(I),G$,OP(I),RT(I)
650 NEXT
660 LPRINT
670 LPRINT
680 LPRINT
690 GOTO 1450
700 INPUT "How many levels of water pressure are you interested in?
    (1-4) ",N
710 IF N<1 OR N>4 THEN PRINT "  Invalid entry, try again...": GOTO 700
720 FOR I=1 TO N
730 INPUT "  Enter a water pressure to evaluate (80-200 psi)", P(I)
740 IF P(I)<80 OR P(I)>200 THEN PRINT "Invalid entry, try again...": GOTO 730
750 NEXT
760 PRINT
770 INPUT "Enter your average spray water flow (15-35 gpm)  ",G
780 IF G<15 OR G>35 THEN PRINT "Invalid entry, try again...": GOTO 770
790 INPUT "Enter your average face airflow (3000-9000 cfm)  ",CFM
800 IF CFM<3000 OR CFM>9000 THEN PRINT "Invalid entry, try again...": GOTO 790
810 C=CFM/100
820 PRINT
830 FOR I=1 TO N
```

```
840 OP(I) = 28.75 - .4485*G - 9.281601E-02*P(I) - .401194*C + .000354*P(I)*C + .00897*G^2 + .000225*P(I)^2
     + .002125*C^2
850 RT(I) = 65.44306 - .764053*G - .324973*P(I) - .406892*C + .002181*G*P(I) + .004814*G*C + .001022*P(I)*C
     + .000578*P(I)^2
860 NEXT
870 PRINT "Predicted dust levels in mg/m3 at "G" gpm and "CFM" cfm:"
880 PRINT
890 PRINT "Pressure","Operator","Return"
900 FOR I=1 TO N
910 P$=" psi"
920 PRINT USING "###&          ##.##          ##.##";
     P(I),P$,OP(I),RT(I)
930 NEXT
940 PRINT
950 INPUT "Would you like these results printed? (1=yes 2=no) ",PR
960 IF PR<1 OR PR>2 THEN PRINT "Invalid entry, try again...": GOTO 950
970 IF PR=2, GOTO 1450
980 LPRINT "Predicted dust levels in mg/m3 at "G" gpm and "CFM" cfm:"
990 LPRINT
1000 LPRINT "Pressure","Operator","Return"
1010 FOR I=1 TO N
1020 LPRINT USING "###&          ##.##          ##.##";
     P(I),P$,OP(I),RT(I)
1030 NEXT
1040 LPRINT
1050 LPRINT
1060 LPRINT
1070 GOTO 1450
1080 INPUT "How many levels of face airflow are you interested in?
     (1-4)  ",N
1090 IF N<1 OR N>4 THEN PRINT "Invalid entry, try again...": GOTO 1080
1100 FOR I=1 TO N
1110 INPUT "Enter an airflow quantity to evaluate (3000-9000 cfm) ", CF(I)
1120 IF CF(I)<3000 OR CF(I)>9000 THEN PRINT "Invalid entry, try again...": GOTO 1110
1130 C(I)=CF(I)/100
1140 NEXT
1150 PRINT
1160 INPUT "Enter your average spray water flow (15-35 gpm) ", G
1170 IF G<15 OR G>35 THEN PRINT "Invalid entry, try again...": GOTO 1160
1180 INPUT "Enter your average spray pressure (80-200 psi) ",P
1190 IF P<80 OR P>200 THEN PRINT "Invalid entry, try again...": GOTO 1180
1200 PRINT
1210 FOR I=1 TO N
1220 OP(I) = 28.75 - .4485*G - .092816*P - .401194*C(I) + .000354*P*C(I) + .00897*G^2 + .000225*P^2
     + .002125*C(I)^2
1230 RT(I) = 65.44306 - .764053*G - .324973*P - .406892*C(I) + .002181*G*P + .004814*G*C(I) + .001022*P*C(I)
     + .000578*P^2
1240 NEXT
1250 PRINT "Predicted dust levels in mg/m3 at "G" gpm and "P" psi:"
1260 PRINT
1270 PRINT "Airflow","Operator","Return"
1280 FOR I=1 TO N
1290 C$=" cfm"
```

```
1300 PRINT USING "####&        ##.##          ##.##";
     CF(I),C$,OP(I),RT(I)
1310 NEXT
1320 PRINT
1330 INPUT "Would you like these results printed? (1=yes 2=no) ",PR
1340 IF PR<1 OR PR>2 THEN PRINT "   Invalid entry, try again...": GOTO 1330
1350 IF PR=2, GOTO 1450
1360 LPRINT "Predicted dust levels in mg/m3 at "G" gpm and "P"  psi:"
1370 LPRINT
1380 LPRINT "Airflow","Operator","Return"
1390 FOR I=1 TO N
1400 LPRINT USING "####&        ##.##          ##.##";
     CF(I),C$,OP(I),RT(I)
1410 NEXT
1420 LPRINT
1430 LPRINT
1440 LPRINT
1450 PRINT
1460 INPUT "Would you like to make additional estimates? (1=yes 2=no)  ",Z
1470 IF Z<1 OR Z>2 THEN PRINT "Invalid entry, try again...": GOTO 1460
1480 PRINT
1490 IF Z=1, GOTO 280
1500 PRINT "Session Completed"
1510 END
```

APPENDIX B.—SAMPLING DATA

Table B-1.—Summary of normalized gravimetric dust concentrations at operator's position in box cut

Waterflow, gpm	Water pressure, psi	Airflow, cfm	Normalized dust level, mg/m³				
			1st test	2d test	3d test	Average	Standard deviation
15	80	3,000	7.43	8.40	8.78	8.20	0.70
15	80	9,000	.49	.02	.17	.23	.24
15	140	6,000	.87	.78	.23	.63	.35
15	200	3,000	4.96	4.94	8.20	6.03	1.88
15	200	9,000	.04	.14	.01	.06	.07
25	80	6,000	.21	.22	.22	.22	.01
25	140	3,000	.64	4.95	2.36	2.65	2.17
25	140	6,000	.42	.13	.52	.36	.20
25	140	6,000	.51	.20	.34	.35	.16
25	140	6,000	11.46	.11	.15	[1].13	[1].03
25	140	9,000	.15	.20	.08	.14	.06
25	200	6,000	.83	.18	.50	.50	.33
35	80	3,000	6.87	9.04	7.36	7.76	1.14
35	80	9,000	.12	.10	.17	.13	.04
35	140	6,000	.50	.36	.55	.47	.10
35	200	3,000	3.82	5.79	4.76	4.79	.99
35	200	9,000	.18	.24	.34	.25	.08

[1]11.46 from first test in series excluded from calculations.

Table B-2.—Summary of normalized gravimetric dust concentrations at operator's position in slab cut

Waterflow, gpm	Water pressure, psi	Airflow, cfm	Normalized dust level, mg/m³				
			1st test	2d test	3d test	Average	Standard deviation
15	80	3,000	1.26	3.75	1.74	2.25	1.32
15	80	9,000	.04	.01	.00	.02	.02
15	140	6,000	.83	2.26	2.56	1.88	.92
15	200	3,000	3.60	7.72	7.03	6.12	2.21
15	200	9,000	.07	.00	.00	.02	.04
25	80	6,000	1.76	.43	1.63	1.27	.73
25	140	3,000	2.92	2.34	4.07	3.11	.88
25	140	6,000	.06	.31	.48	.28	.21
25	140	6,000	.25	.24	.39	.29	.08
25	140	6,000	.11	.42	1.19	.57	.56
25	140	9,000	.05	.00	.00	.02	.03
25	200	6,000	.10	1.09	.61	.60	.50
35	80	3,000	3.41	2.76	.96	2.38	1.27
35	80	9,000	.09	.00	.05	.05	.05
35	140	6,000	.04	.47	.63	.38	.31
35	200	3,000	.30	1.21	.57	.69	.47
35	200	9,000	.19	.21	.51	.30	.18

Table B-3.—Summary of normalized gravimetric dust concentrations for return location in box cut

Waterflow, gpm	Water pressure, psi	Airflow, cfm	Normalized dust level, mg/m^3				
			1st test	2d test	3d test	Average	Standard deviation
15	80	3,000	27.20	26.61	29.26	27.69	1.39
15	80	9,000	13.67	11.23	10.49	11.80	1.66
15	140	6,000	14.66	14.21	7.75	12.21	3.87
15	200	3,000	13.46	12.85	17.35	14.55	2.44
15	200	9,000	7.87	7.14	6.49	7.17	.69
25	80	6,000	14.98	13.94	13.89	14.27	.62
25	140	3,000	14.23	11.13	18.32	14.56	3.61
25	140	6,000	13.75	11.49	7.59	10.94	3.12
25	140	6,000	12.47	10.95	10.40	11.27	1.07
25	140	6,000	12.39	12.95	7.38	10.91	3.07
25	140	9,000	7.02	9.62	7.87	8.17	1.33
25	200	6,000	13.47	9.98	8.52	10.66	2.54
35	80	3,000	18.44	17.62	19.71	18.59	1.05
35	80	9,000	9.00	8.87	8.68	8.85	.16
35	140	6,000	12.45	9.68	9.42	10.52	1.68
35	200	3,000	12.33	10.23	12.09	11.55	1.15
35	200	9,000	8.45	6.97	8.58	8.00	.89

Table B-4.—Summary of normalized gravimetric dust concentrations for return location in slab cut

Waterflow, gpm	Water pressure, psi	Airflow, cfm	Normalized dust level, mg/m^3				
			1st test	2d test	3d test	Average	Standard deviation
15	80	3,000	17.16	19.48	23.69	20.11	3.31
15	80	9,000	9.08	12.17	13.51	11.59	2.27
15	140	6,000	12.43	13.52	12.95	12.97	.55
15	200	3,000	11.51	14.84	14.70	13.68	1.88
15	200	9,000	10.04	10.65	11.31	10.67	.64
25	80	6,000	14.46	12.00	17.29	14.58	2.65
25	140	3,000	15.46	12.72	14.00	14.06	1.37
25	140	6,000	10.66	11.26	11.82	11.25	.58
25	140	6,000	11.53	11.91	10.70	11.38	.62
25	140	6,000	11.37	10.86	13.27	11.83	1.27
25	140	9,000	10.06	9.74	9.61	9.81	.23
25	200	6,000	9.92	10.54	8.95	9.80	.80
35	80	3,000	18.18	17.23	15.56	16.99	1.33
35	80	9,000	12.39	10.42	11.20	11.34	.99
35	140	6,000	7.95	9.77	10.40	9.37	1.27
35	200	3,000	9.67	8.77	7.98	8.81	.85
35	200	9,000	8.06	5.23	8.16	7.15	1.66

Table B-5.—Model fitting results for regression analysis

Sampling location and independent variable	Variable coefficient	Standard error value	t-value	Significance level
OPERATOR LOCATION				
Box cut:				
Constant	-0.152841	0.2606	-0.587	0.5605
Water pressure (psi)	-.008576	.0032	-2.683	.0102
Airflow (cfm)	-.096634	.0064	-15.008	.0000
Water pressure × airflow (psi•cfm)	.000354	.0001	2.950	.0051
Waterflow, squared (gpm^2)	.008970	.0035	2.551	.0143
Water pressure, squared (psi^2)	.000225	.0001	2.221	.0315
Airflow, squared (cfm^2)	.002125	.0004	5.228	.0000
Slab cut:				
Constant	.722595	.2093	3.452	.0012
Waterflow (gpm)	.068428	.0183	-3.743	.0005
Airflow (cfm)	.046939	.0058	-8.072	.0000
Waterflow × water pressure (gpm•psi)	-.001119	.0003	-3.288	.0020
Waterflow × airflow (gpm•cfm)	.002313	.0007	3.430	.0013
Airflow, squared (cfm^2)	.000868	.0003	2.896	.0058
RETURN LOCATION				
Box cut:				
Constant	11.200041	0.4241	26.411	0.0000
Waterflow (gpm)	-.169873	.0364	-4.673	.0000
Water pressure (psi)	-.047288	.0059	-7.983	.0000
Airflow (cfm)	-.143462	.0119	-12.078	.0000
Waterflow × water pressure (gpm•psi)	.002181	.0007	3.191	.0026
Waterflow × airflow (gpm•cfm)	.004814	.0014	3.490	.0011
Water pressure × airflow (psi•cfm)	.001022	.0002	4.603	.0000
Airflow, squared (psi^2)	.000578	.0002	3.760	.0005
Slab cut:				
Constant	11.423097	.2912	39.234	.0000
Waterflow (gpm)	-.167039	.0254	-6.573	.0000
Water pressure (psi)	-.040634	.0041	-9.975	.0000
Airflow (cfm)	.076354	.0081	-9.445	.0000
Waterflow × water pressure (gpm•psi)	.000981	.0005	-2.072	.0443
Waterflow × airflow (gpm•cfm)	.001905	.0009	2.032	.0484
Water pressure × airflow (psi•cfm)	.000641	.0002	4.253	.0001
Water pressure, squared (psi^2)	.000309	.0001	2.923	.0055